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Combining simultaneous with temporal masking

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Simultaneous and temporal masking are two frequently used techniques in psychology and vision science. While there are many studies and theories related to each masking technique, there are no systematic investigations of their mutual relationship, even though both techniques are often applied together. Here, we show that temporal masking can both undo and enhance the deteriorating effects of simultaneous masking depending on the stimulus onset asynchrony between the simultaneous and temporal mask. For the task and stimuli used in this study, temporal masking was largely unaffected by the properties of the simultaneous mask. In contrast, simultaneous masking seems to depend strongly on spatial grouping and was strongly affected by the properties of the temporal mask. These findings help to identify the nature of both temporal and simultaneous masking and promote understanding of the role of spatial and temporal grouping in visual perception.

Keywords: backward masking, metacontrast

In visual masking, the visibility of a target stimulus can be strongly reduced when a mask is presented simultaneously with the target (simultaneous masking) or when the mask precedes or follows the target (temporal forward or backward masking, respectively). While both types of masking have a long history of study, they are usually treated as separate phenomena. Each of these two masking types subscribes to different modeling approaches, explanations, and philosophies. For example, theories of simultaneous masking often subscribe to filter-based models relying on feed-forward information processing using static lateral inhibition or feature pooling (e.g. Foley & Chen, 1999; Wilkinson, Wilson, & Ellemberg, 1997). Simultaneous masking was used to isolate the excitatory and inhibitory nonlinear spatial interactions involved in contrast detection. In contrast, theories of temporal masking tend to employ dual channels with different time constants (e.g. Bachmann, 1994; Breitmeyer & Öğmen, 2006; Öğmen, 1993) or recurrent connections (e.g. Di Lollo, Enns, & Rensink, 2000) and emphasize how the relative timing of stimuli affects the processing of the target.

Masking inherently involves both spatial aspects (such as the size of the stimuli and their relative separation) and temporal aspects (such as the duration of the stimuli and the relative timing), but usually one of these aspects is neglected while the other is studied. In simultaneous masking, the spatial properties of the target and the mask are varied, while the timing is kept constant, whereas in temporal masking, the focus has been on the temporal aspects of the target-mask sequence. However, both past and recent research suggests that such separation of spatial or temporal aspects is not tenable (Duangudom, Francis, & Herzog, 2007; Francis & Herzog, 2004; Francis, 2007; Herzog, 2007; Weisstein & Bisaha, 1972). For example, Duangudom, Francis and Herzog (2007) demonstrated that changes in the spatial layout of the mask, such as increasing or decreasing the length of its elements, can have profound effects on temporal aspects. In particular, the shape of the masking function, linking performance and the stimulus onset asynchrony (SOA) between the target and the mask, could be changed by changing the spatial layout of the mask. Such findings have implications not just for experimental work on masking, but also for theories and models. Clearly, theories of simultaneous masking that lack a temporal component cannot account for the delicate timing of spatial processing (e.g. Francis, 2000; Herzog, 2007; Saarela & Herzog, 2008). On the other hand, most backward masking models lack explicit spatial processing and, thus, cannot explain the complex effects of the spatial layout of stimuli on masking strength (however see Francis, 1997; Hermens, Luksys, Gerstner, Herzog, & Ernst, 2008; Öğmen, 1993). Hence, the current division between temporal masking, predominantly focussed on temporal aspects, and simultaneous masking, studying spatial aspects only, should be abandoned. Instead, the two types of masking (simultaneous and temporal) should be studied together (Herzog, 2007).

Studying the interaction between temporal and simultaneous masking is particularly important because the two masking techniques are often used together as a tool to explore aspects of perception and cognition. For example, in lan-

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guage perception studies (e.g. Grainger, Bouttevin, Truc, Bastien, & Ziegler, 2003), a brief target letter is presented either in the context of letters making up a word or a nonword (where the letters around the target act as a simultaneous mask), which is followed by a mask composed of letters or other symbols, such as hash marks (serving as a backward mask). Studies on texture processing also implicitly include both simultaneous and temporal masking. Often a target texture is embedded in a background texture and then followed by a textured mask (e.g. Caputo, 1998; Karni & Sagi, 1993; Schubö, Schlaghecken, & Meinecke, 2001). Significantly, these uses of masking do not often explicitly identify the different types of masking used, and the precise effects of the different masks are often unspecified.

Besides using masking as a tool to limit the amount of available information or to interrupt information processing, masking has been widely used to investigate the basic processes underlying visual perception, and in particular whether the visual system relies on feed-forward or recurrent processes to identify a stimulus (e.g. Macknik & Martinez-Conde, 2007). Another aspect of importance in visual perception involves the way the brain groups information over time and space. A long-standing debate involves whether grouping occurs early in visual processing or whether extensive processing of the visual image is needed (Palmer, Brooks, & Nelson, 2003). In previous modeling work, we have demonstrated that simply defined lateral excitatory and inhibitory dynamic interactions are sufficient to explain complex grouping processes (Hermens et al., 2008; Hermens, Scharnowski, & Herzog, in press; Herzog, Ernst, Etzold, & Eurich, 2003). These model interactions have such simple interactions that it is plausible that they occur in the early stages of visual information processing, such as the computations carried out in primary visual cortex (see Li, 2000; Zhaoping, 2003). These grouping processes have been identified empirically by the impact that grouping has on the visibility of a briefly presented target stimulus when presented with either a temporal or a simultaneous mask (e.g. Hermens et al., in press; Herzog, Fahle, & Koch, 2001; Herzog, Schmonsees, Boesenberg, Mertins, & Fahle, 2008). The current experiments add to the evidence that grouping might be an early visual process by exploring how grouping of the elements of a temporal and a simultaneous mask determines the visibility of a briefly presented target element.

To summarize, many studies in psychology use both simultaneous and backward masking to explore perceptual and cognitive processing. However, there is currently no theory of masking that indicates how these different mask types combine to affect a target stimulus. In the experiments below, we will systematically investigate simultaneous and backward masking and show that existing theories of masking need to be extended because they fail to explain the complex ways in which the two mask types interact.

General Methods

Participants

Fourteen participants took part in the experiments. Except for two authors (FH and GF), all participants were students at the École Polytechnique Fédérale de Lausanne (EPFL) or the University of Lausanne.

Before taking part in the experiments, participants first signed an informed consent form and performed the Freiburg visual acuity test (Bach, 1996). To participate in the experiments, observers had to reach a value of 1.0 (corresponding to 20/20) for at least one eye. Students were paid 20 CHF (about 13 Euro) per hour. The experiments were approved by the local ethics committee.

Apparatus

Stimuli were presented on an X-Y display (HP-1332A or Tektronix 608) with a bluish phosphor (P11). The display was controlled by a PC via fast 16-bit DA converters. Line elements were composed of dots drawn at a dot pitch of 200μm and a dot rate of 1 MHz. The display was refreshed at a rate of 200 Hz, which means that stimuli of 20 ms were presented in four refresh cycles of 5 ms each. The luminance of the stimuli was set to 80 cd/m^2, as determined with a Minolta LS-100 luminance meter. The luminance of the background was less than 1 cd/m^2.

Stimuli

Vernier stimuli consisted of two vertical line segments that were either 10' (arc minutes) or 20' in height. Line segments were vertically separated by a gap of 1'. The vernier segments were either aligned (verniers in the mask) or horizontally offset (the target vernier). The simultaneous mask consisted of 24 aligned verniers (12 on each side of the target vernier, see Figure 1). The center-to-center spacing between these mask elements was 3.3', as was the distance of the nearest element to the center of the target. The temporal mask consisted of a single aligned vernier, which was centered at the same location as the target, and presented at different stimulus onset asynchronies. The height of both the simultaneous and the temporal mask elements was varied across experiments. Each stimulus was presented for 20 ms.

Before each trial, a fixation screen was shown, which consisted of a small fixation cross at the center and four markers in each of the corners. At the top of the screen, a small line indicated progress within a block of trials.

Design

In all experiments, we varied the onset of the temporal mask relative to the onset of the target and simultaneous mask. In the first experiment, we used stimulus onset asynchronies (SOAs) of -200, -120, -60, -30, -20, 0, 20, 30, 60, 120, 200ms between the target and the temporal mask. In successive experiments, a coarser set of SOAs was used (-200, -60, -20, 0, 20, 60, 200ms). Performance was determined blockwise (80 trials) per SOA. Within a block, the offset direction of the target vernier (left, right) was varied randomly for each trial, and the offset size of the target was varied according to an adaptive staircase procedure (PEST, Taylor & Creelman, 1967). On the basis of 80 trials, an offset discrimination threshold for the target vernier was estimated as the spatial offset at which the participant obtained 75% correct responses. After all SOAs were run once, they were repeated in the opposite order and the resulting thresholds were pooled to counteract effects of fatigue and practice. The order of the SOAs was randomized across participants.

Procedure

Each participant was seated at a distance of 2 meters from the display. On each trial, the participant indicated the offset direction of the target vernier (the position of the lower segment with respect to the top segment) by pressing the corresponding one of two push buttons. The participant was asked to guess when unsure. A beep followed an incorrect response. If no response was given within 3000ms, the trial was repeated at the end of the block.

The first experiment was performed in two sessions of about one hour each. The remaining experiments were performed in one session of a bit more than one hour.

Data analysis

For the statistical comparison between conditions, a non-parametric paired sample Wilcoxon signed rank test was used. A non-parametric test was used to be able to compare the stability of the differences across conditions within each participant without being biased by the differences across participants.

Experiment 1

The first experiment explored how interactions between a temporal mask and a simultaneous mask affected target vernier thresholds.

Methods

Five participants took part in Experiment 1. Two authors participated. The remaining three participants were naive with respect to the purpose of the experiment. As schematized in Figure 1, the *simultaneous* mask consisted of 24 straight verniers that flanked the central target vernier. The *temporal* mask was a single straight vernier that was presented at various SOAs relative to the target. With an SOA of zero, the temporal mask filled in the 'missing' central element of the simultaneous mask, and overlapped with the target vernier except for the offset. All vernier elements (target and mask) were 21' in height, consisting of two lines of 10' with a gap of 1'. There were also two control blocks; one with no masks at all and one with only the simultaneous mask.

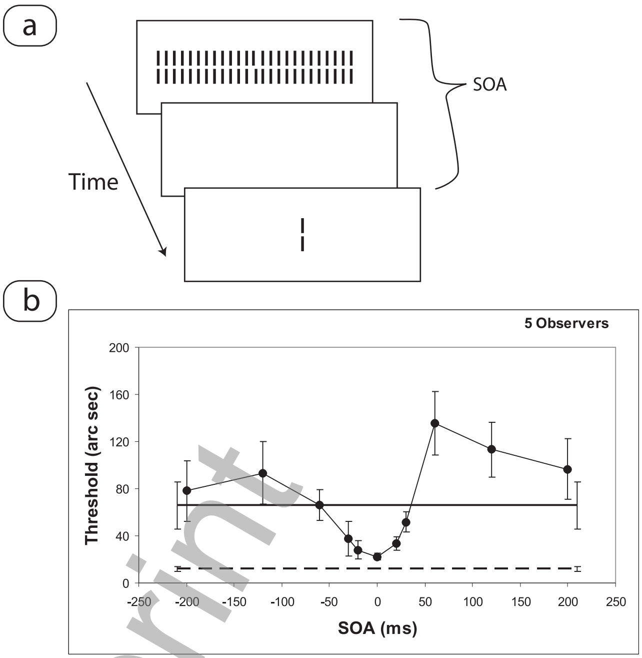

Figure 1. **a.** The stimulus sequence used in Experiment 1. A central vernier target was surrounded by a simultaneous mask of 24 straight verniers (twelve on each side). A central straight vernier, presented at a variable SOA, served as a temporal mask and was presented before the target and the simultaneous mask (not shown) or afterwards (as shown here). **b.** Vernier offset discrimination thresholds as a function of the SOA between the target and the temporal mask. The horizontal dashed line shows performance for the target vernier without any mask. The horizontal solid line shows performance without the temporal mask, i.e. simultaneous masking only. Error bars indicate the standard error of the mean across five observers. Negative SOA values indicate forward masking (the mask precedes the target), positive values indicate backward masking (the mask follows the target).

Results

Figure 1b plots target offset thresholds against SOA. The dashed horizontal line shows performance when only the target vernier is presented. The solid horizontal line shows performance when, in addition, the simultaneous mask is presented. Clearly, adding this mask increases thresholds substantially (Wilcoxon signed rank test for paired samples, z=-2.023, p=0.043; two-tailed).

The filled circles show thresholds when both the simultaneous mask and the temporal mask are presented. The effect of the temporal mask strongly depends on the SOA. Around an SOA of 0ms, the temporal mask actually *reduces* thresholds, i.e. weakens masking, compared to the condition with only the simultaneous mask (z=-2.023, p=0.043; two-tailed). Performance with both masks presented at an SOA of zero approaches that of the condition in which the target vernier is presented alone (dashed line). For all SOAs, the temporal mask increases masking with respect to the zero SOA. For a range of about 100ms, performance remains below that for the target with only the simultaneous mask (SOAs of -60ms to 40ms). At SOAs outside the interval between -60 and 40ms, the temporal mask leads to a further elevation of the threshold above that generated by the simultaneous mask alone. Peak masking occurs around -120ms and 60ms for the forward and backward masking conditions, respectively. Masking effects do not entirely vanish at SOAs less than -200ms (forward masking) or longer than 200ms (backward masking).

Discussion

The threshold elevation of the target by only the simultaneous mask is consistent with the findings of Malania, Herzog, and Westheimer (2007) (see also Westheimer & Hauske, 1975), who suggested that the threshold elevation is due to the grouping of the target vernier with the elements of the simultaneous mask.

Depending on the SOA, the temporal mask can increase or decrease performance compared to when only the target vernier and simultaneous mask are presented. Masking is weakest at an SOA of 0ms. We suggest that this is because adding the temporal mask to the simultaneous mask creates a regular grating. Because of this, the target vernier no longer groups with the simultaneous mask. This leads to ‘freeing’ of the target vernier from the simultaneous mask, and it can therefore be better discriminated. Such an interpretation agrees with the subjective experience. The vernier target appears to be brighter with the temporal mask presented at SOA of 0ms and stands out from the other elements in the grating. This can be explained by the summation of the luminance of the vernier target and the central element of the grating (we will return to the different possible explanations in the General Discussion).

As with the SOA of 0ms, we propose that due to temporal integration, the temporal mask groups with the simultaneous mask at all SOAs near 0ms, resulting in thresholds that are lower compared to when the target and simultaneous mask are presented without a temporal mask. The window of integration across which the temporal and the simultaneous mask group, seems to be 100ms long, lasting from -60ms to 40ms. The more the SOA deviates from zero, the less likely the simultaneous and temporal masks group together and instead the target vernier is bound to the elements of the simultaneous mask, thereby resulting in higher thresholds. For longer SOAs, thresholds with the temporal mask are higher than those for just the simultaneous mask. We attribute this additional effect of the temporal mask to interruption masking. The temporal mask thereby interrupts the processing of the combination of the target and the simultaneous mask. This effect of the temporal mask persists for unusually long SOAs, i.e. up to at least -200ms in forward masking and beyond 200ms in backward masking. This is a surprising finding, because with the simple kind of task we use and similar high contrast stimuli, performance usually reaches baseline level much earlier (e.g., Breitmeyer & Öğmen, 2006). The temporal mask may have such a long lasting effect, because the simultaneous mask forces the observer to integrate information over a greater duration, thereby exposing the target vernier to interference from the temporal mask over a much longer intervals.

Often, masking becomes weaker by delaying the presentation of a spatially overlapping mask (however, see Hellige, Walsh, Lawrence, & Prasse, 1979; Turvey, 1973). This situation, in which masking is strongest at a zero SOA, is referred to as A-type masking. Our spatially overlapping temporal mask, however, results in a different pattern of results. Masking is weak (even facilitory) at short SOAs (<60ms) after which it peaks at an intermediate SOA to become weaker again for longer SOAs (>60ms). Masking that follows this pattern is called B-type. As we will show in Experiment 2, B-type masking with the pattern mask that we used, is tied to the use of a simultaneous mask. This indicates that a simultaneous mask can affect the type of masking found. Also for the forward masking situation (SOAs< 0), we found the strongest masking at a non-zero SOAs. Although such B-type masking is regularly found in backward masking, it is much less frequently observed in forward masking (exceptions include Breitmeyer, Ziegler, & Hauske, 2007; Green, Nuechterlein, Breitmeyer, & Mintz, 2006; Öğmen, Breitmeyer, & Melvin, 2003). Two of the studies that found Type-B forward masking showed strongest masking at a value comparable to ours (Breitmeyer et al., 2007; Green et al., 2006)

In the following experiments, we demonstrate that the simultaneous and temporal masks have separate effects on the target, but that the masking effects of both types of masks depends on their mutual interactions.

Experiment 2

In Experiment 2, we show that the temporal mask by itself hardly has an effect on target vernier offset discrimination. This indicates that it is the combination of the simultaneous and the temporal mask that yields the strongly modulated masking strength across the SOAs in Experiment 1.

Methods

Five participants took part in Experiment 2. Four of these participants also took part in Experiment 1. One naive participant joined in addition. The stimulus sequence of Experiment 2 is illustrated in Figure 2a: A vernier target was followed or preceded by an aligned vernier at a variable SOA. No simultaneous mask was used. Both the target and the mask were 21’ in height.

Results and discussion

Figure 2b shows that the temporal mask presented without the simultaneous mask, yields only weak masking, i.e. thresholds are only slightly elevated compared to the vernier alone condition. Collapsing across all SOAs, the target thresholds were higher with the temporal mask compared to the no-mask situation ($z=-2.023$, $p=0.043$; two-tailed). Although masking seems to be stronger at longer SOAs, thresholds are not significantly higher than those at short SOAs

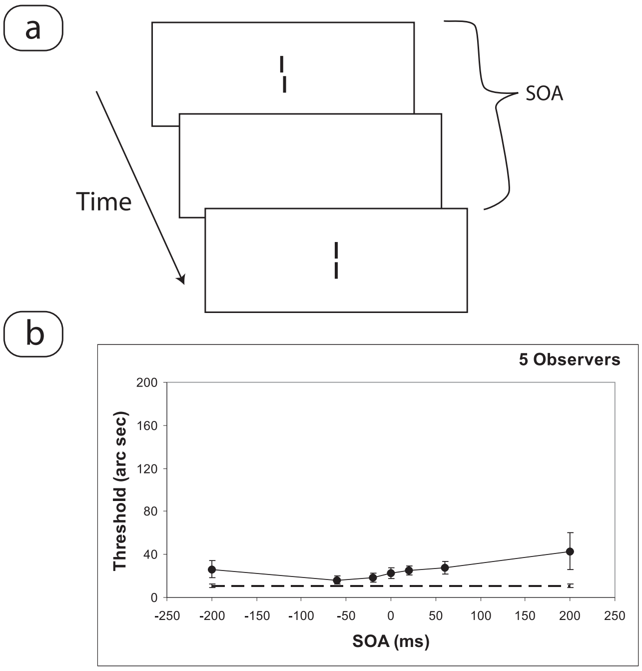

Figure 2. **a.** The stimulus sequence used in Experiment 2. The offset vernier target was followed or preceded by a straight vernier at a variable SOA. **b.** Vernier offset discrimination thresholds as a function of the SOA between the target and the mask. The horizontal dashed line shows performance for just the vernier target. Error bars indicate the standard error of the mean across observers.

(e.g., z=-0.674, p=0.50; two-tailed, SOA=-200/200ms versus SOA=0ms).

It is clear that the effects of the temporal mask by itself are completely different from those in the situation in which the temporal mask is presented in conjunction with the simultaneous mask. Not only is masking much weaker in the absence of the simultaneous mask, but also the pattern of masking as a function of the SOA is completely different.

Experiment 3

We argued that the facilitative effects of the temporal mask in Experiment 1 were due to the integration of the temporal mask with the simultaneous mask, thereby creating a regularly spaced grating. This completion releases the target vernier from the effects of the simultaneous mask. In Experiment 3, we provide additional evidence for this claim by showing that the facilitative effects of the temporal mask disappear when neither the target nor the temporal mask groups with the simultaneous mask.

Previous research showed that increasing the length of the elements of the simultaneous mask improves performance compared to the situation in which elements of the simultaneous mask have the same length as the vernier (Malania et al., 2007; Duangudom et al., 2007). It was argued that by increasing the length of the mask's elements beyond that of the vernier, the vernier is released from grouping with the simultaneous mask. If our hypothesis is correct, using a simultaneous mask with elements longer than the target should mean that the temporal mask no longer has a facilatory effect at short SOAs.

Methods

Five participants took part in Experiment 3. Two of them had also taken part in Experiments 1 and 2, whereas the remaining three participants had no previous experience with the paradigm. The target vernier was surrounded by 24 aligned verniers of twice the length of the target vernier (i.e. segments were 20' in height instead of 10', thus the vernier was 41' including the gap of 1'). The temporal mask was of the same height as the target, i.e. 21', and was presented at a variable SOA with respect to the target and the simultaneous mask (see Figure 3a).

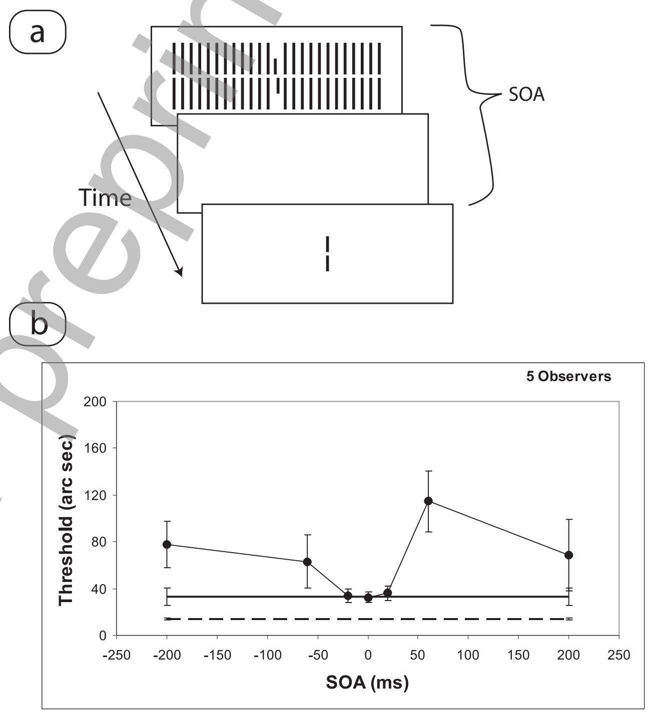

Figure 3. **a.** The stimulus sequence used in Experiment 3. A central vernier target was surrounded by a simultaneous mask of 24 straight verniers with double the length of the target. At a variable SOA, the straight masking line (the temporal mask) was presented. **b.** Vernier offset discrimination thresholds as a function of the SOA between the target and the temporal mask. The horizontal dashed line shows performance for the target vernier without any mask. The horizontal solid line shows performance when the simultaneous mask and the vernier are presented (without the temporal mask). Error bars indicate the standard error of the mean across observers.

Results

Figure 3b plots the average thresholds across the five observers. The dashed horizontal line shows performance for the target vernier without any mask. The solid horizontal line indicates the target threshold when the simultaneous mask was also presented. As expected, thresholds for the longer simultaneous masks are lower than those by a mask with elements equal in length to the target (Figure 1b). In fact, thresholds for the simultaneous mask alone approach those for the vernier only condition (the increase due to the simultaneous mask is only marginally significant: $z=1.753$; $p=0.080$; two-tailed). Moreover, adding the temporal mask does not yield facilitation for any SOA (all thresholds are at or above that for the simultaneous mask alone condition).

To demonstrate that increasing the length of the simultaneous mask elements only results in a decrease of the baseline, we compare the results of Experiments 1 and 3 in Figure 4. Increasing the length of the simultaneous mask elements lowered the threshold of the target vernier from approximately 70 arcseconds (dashed line) to 30 arcseconds (dotted line) when no temporal mask is presented (for the two participants that performed both tasks, thresholds went down by 47% and 92%). This decrease in thresholds by increasing the length of the mask's elements replicates earlier findings by Duangudom, Francis, & Herzog (2007, Figure 3, SOA=0) and Malania, Herzog, & Westheimer (2007, Figure 3, 16 flanks). Whereas the threshold changed in the condition with just the simultaneous mask, thresholds as a function of SOA with the temporal mask hardly changed by increasing the length of the simultaneous mask's elements. The two curves for forward and backward masking are nearly superimposed, whereas there is a clear difference in baseline performance generated by only the simultaneous mask.

Discussion

A comparison of the results of Experiment 1 and 3 reveals that the effect of the temporal mask is essentially independent of the length of the elements of the simultaneous mask. As experiment 2 showed, however, the presence of a simultaneous mask is necessary for the temporal mask to have any masking effect at all. This means that although there is a strong interaction between the simultaneous and the temporal mask, the exact shape of the simultaneous mask is not critical.

The experiments imply that at least two different mechanisms are at work in masking. At SOAs near zero, one mechanism involves the grouping of the temporal mask with the simultaneous mask. Such grouping only occurs when the temporal mask and the elements of the simultaneous mask are similar in shape. If the target was originally bound to the simultaneous mask, the grouping of the two masks releases the target vernier from simultaneous masking. The second mechanism, quite to the contrary, enhances the effect of the simultaneous mask for substantial periods of time, resulting in thresholds well above those obtained with just the simultaneous mask. Although we suspect that some type of interruption masking is taking place, the exact mechanism of this enhancement remains unclear to us.

The comparison of the results of Experiment 1 and 3 demonstrate that conclusions about the underlying mechanisms of masking need to be drawn with care from the experimental data. The results of Experiment 1, by themselves, could have been interpreted as evidence that at SOAs near zero, the temporal mask improves target offset processing. However, the comparison of the results of Experiments 1 and 3 suggests that, in fact, grouping of the temporal mask with the simultaneous mask at SOAs near 0ms removes the simultaneous masking effects. Such grouping occurs only for short SOAs because at these SOAs the simultaneous and the temporal masks temporally integrate together.

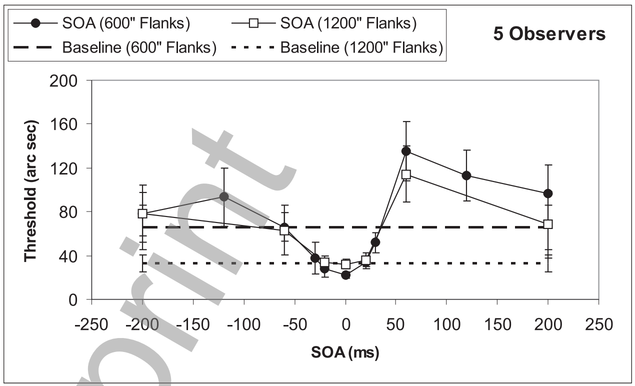

Figure 4. A comparison of the thresholds of Experiments 1 and 3, in which the length of the simultaneously presented flanks was different (10' and 20', respectively). The target had the same length, i.e. 10', in both conditions. The data show that only the baseline of the simultaneous masking conditions changes if the length of the flankers is changed. However, the effect of the temporal mask remains virtually the same.

Experiment 4

We argued that no facilitatory effects of the temporal mask were found in Experiment 3 because the temporal mask did not group with the simultaneous mask, due to a difference in element length. From this argument, one would predict that similar masking effects should occur if the lengths of the two masks are reversed. We tested this prediction in Experiment 4, in which the simultaneous mask is unchanged from Experiment 1, but the temporal mask is doubled in length, which prevents it from grouping with the simultaneous mask. This experiment also tests whether the additional luminance by the temporal mask a short SOAs results in weakened masking.

Methods

Four participants took part in the experiment. The stimulus sequence is illustrated in Figure 5a. The same simultaneous mask was used as in Experiment 1, with elements of equal height as the target. The temporal mask was a single straight vernier with lines twice the length of the target vernier.

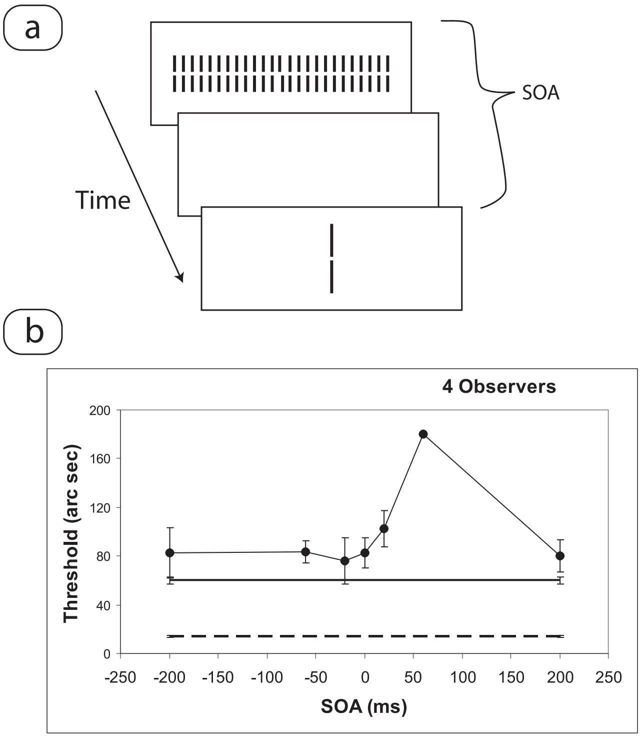

Figure 5. **a.** The stimulus sequence used in Experiment 4. A central vernier target was surrounded by a simultaneous mask of 24 straight verniers having the same length as the vernier. At a variable SOA, the temporal mask, a central straight vernier with double the length of the target, was presented. **b.** Vernier offset discrimination thresholds as a function of the SOA between the target and the temporal mask. The horizontal dashed line shows performance for the target vernier without any mask. The horizontal solid line shows performance for the vernier presented with just the simultaneous mask. Error bars indicate the standard error of the mean across observers.

Results and Discussion

Figure 5b plots the average thresholds across the four observers. The dashed horizontal line shows performance for a target vernier presented by itself. The solid horizontal line presents the average target threshold when only the vernier and the simultaneous mask were presented without the temporal mask.

We predicted that adding the temporal mask would not produce facilitatory effects relative to the simultaneous mask alone. Figure 5b demonstrates that this prediction is correct (all means are above the threshold of the simultaneous mask alone; z=1.826, p=0.068; two-tailed, comparing the mean across all SOAs against the no temporal mask baseline). We interpret this finding as evidence that the size difference between the temporal mask and the simultaneous mask prevents the two masks from grouping together. Because of this, the temporal mask could not release the target from grouping with the simultaneous mask at short SOAs.

On the other hand, the temporal mask does lead to stronger masking compared to the condition with the simultaneous masking, especially when it is presented as a backward mask (for all participants, thresholds went up to the maximum of 180” for an SOA of 60ms; z=-2.023, p=0.043; two-tailed, SOA=60ms versus baseline). This finding, again, points to different mechanisms involved in simultaneous and temporal masking, since a similar change in the length of the simultaneous mask weakened masking. Notably, the variation in SOA produces essentially the same pattern of results as in Experiments 1 and 3, with only a change in the magnitude of the effects.

The observation that the temporal mask does not decrease thresholds below the one corresponding to the simultaneous mask alone suggests that the additional luminance provided by the temporal mask does not aid discrimination of the target offset.

Experiment 5

To round out our argument that simultaneous masking strongly depends on grouping, we consider the case where the simultaneous and temporal mask elements should group together at short SOAs (because they have the same length), but the target vernier does not group with the simultaneous mask (because it has a different length from the surround). We predict that the temporal mask will have an effect very similar to that in Experiment 4, with no facilitatory effects relative to the simultaneous mask alone.

Methods

Five participants took part in Experiment 5. Two participants were new to the paradigm, whereas the other three observers participated in one or more of the earlier experiments. The stimulus sequence is shown in Figure 6a. The target vernier was surrounded by a simultaneous mask of 24 aligned verniers that were twice as long as the target vernier. The temporal mask was also twice as long as the target vernier and was presented at a variable SOA.

Results

Figure 6b plots the average thresholds across the five observers. The horizontal dashed line shows performance for the target vernier without any mask. The solid horizontal line indicates the target threshold when only the simultaneous mask was flanking the target. As in Experiment 3, increasing the size of the simultaneous mask elements lead to weaker masking compared to the condition in which equal length flanks were used (Experiments 1 and 4), in agreement with earlier findings (Duangudom et al., 2007; Malania et al., 2007). Masking is reduced to a level close to that without a mask (z=1.753, p=0.080; two-tailed). As predicted, the temporal mask does not introduce any facilitatory effects (z=-2.023, p=0.043; two-tailed, average across all SOAs versus baseline). Still, the pattern of results across SOAs is similar to that in the other experiments.

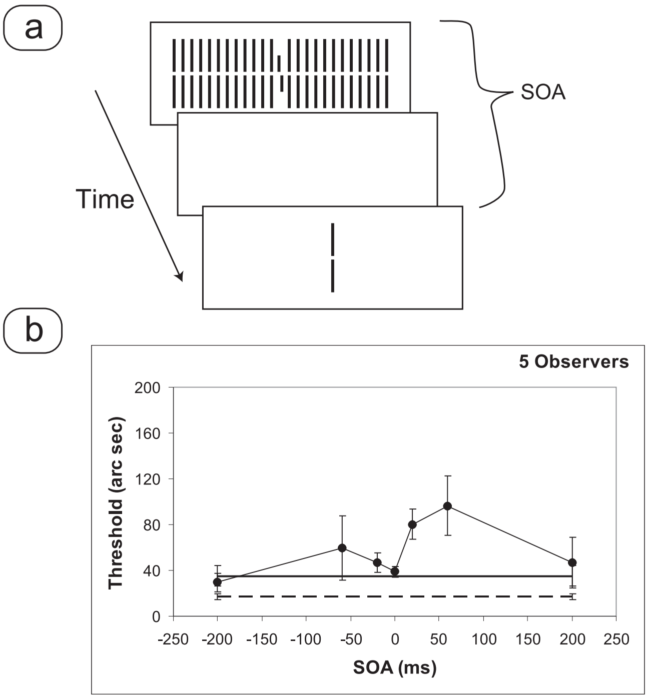

Figure 6. **a.** The stimulus sequence used in Experiment 5. A central vernier target was surrounded by a simultaneous mask of 24 straight verniers with double the length of the target. At a variable SOA, a temporal mask of a central straight vernier, with double the length of the target, was presented. **b.** Vernier offset discrimination thresholds as a function of the SOA between the target and the temporal mask. The horizontal dashed line shows performance for the target vernier alone condition. The horizontal solid line shows performance when the vernier is presented with the simultaneous mask only. Error bars indicate the standard error of the mean across observers.

General discussion

Our experiments demonstrate that simultaneous and temporal masking effects interact in a complex way that might make them difficult to tease apart. In our study, a simultaneous mask with all elements of the same length as the vernier raised thresholds by a factor of more than five compared to when the vernier is presented alone. This threshold elevation can be strongly modulated by adding a temporal mask comprised of one single vernier only. Experiment 1 showed that this temporal mask can either weaken the simultaneous masking effect (for SOAs around zero) or enhance it (for SOAs away from zero). We attributed the weakening to the grouping of the temporal mask with the simultaneous mask: the single, aligned vernier nicely completes the simultaneous mask by filling the central gap. At short SOAs, the temporal mask groups with the simultaneous mask rather than the target vernier because the temporal mask has no offset just as the simultaneous mask (for evidence that small vernier offset differences can be powerful grouping cues, see Hermens et al., in press). For SOAs deviating from 0ms, the grouping of the temporal mask becomes increasingly less likely because temporal dissimilarity increases. When the temporal mask does not group with the simultaneous mask, the target vernier is more likely to group with the simultaneous mask. The window of integration for the temporal and simultaneous masks is about 100ms (SOAs from -60ms to 40ms) which is fairly long. Interestingly, by itself, the temporal mask in our study had almost no masking effect (Experiment 2). It remains to be shown whether other stimuli, such as letters and textures, can analogously be 'freed' from simultaneous masking by a temporal mask.

For SOAs near zero, the vernier often appears wider and brighter than the surrounding elements. This effect was previously reported by (Herzog, Fahle, & Koch, 2001) and termed 'the shine-through effect', because of the appearance of the vernier shining through the mask. It should be noted that in those previous studies, masks were presented for a longer duration and after target disappearance, rather than simultaneously with the target.

The facilitatory effects found in Experiment 1 are reminiscent of disinhibition effects that have been reported in other studies (Breitmeyer, Rudd, & Dunn, 1981; Briscoe, Dember, & Warm, 1983; Dember & Purcell, 1967; Öğmen, Breitmeyer, Todd, & Mardon, 2006; Robinson, 1966; Tenkink, 1983; Tenkink & Werner, 1981). In disinhibition studies, a target stimulus is followed by a mask which is preceded or followed by a second mask. In some circumstances, the second mask can inhibit the first mask and thereby free the target from masking effects. In such experiments, unmasking by the second mask is typically strongest when the second mask is presented after the first mask. In our experiment, unmasking is strongest when the second mask is presented together with the simultaneous mask. We, therefore, suspect that the types of masking, although seemingly similar, are actually based on different mechanisms.

Implications for theories of masking. In other contexts, such as lateral masking and crowding, simultaneous masking effects have been explained by low-level neural mechanisms, such as lateral inhibition, feature pooling (e.g. Westheimer & Hauske, 1975; Wilkinson et al., 1997), or attentional resolution (He, Cavanagh, & Intriligator, 1996). These explanations may not suffice for the stimuli used in the present study, first, because increasing the length of the elements of the simultaneous mask greatly improves performance (see also Duangudom et al., 2007; Malania et al., 2007). Both lateral inhibition and feature pooling explanations would predict that an increase in the length of the simultaneous mask elements would lead to stronger masking (e.g., a stronger inhibitory signal or smaller signal-to-noise ratio due to an increase in noise pooling). Second, as these models mainly focus on spatial aspects, they are not suited to explain the strong modulation of the masking strength by the stimulus onset asynchrony between the target and the temporal mask.

Models of forward and backward masking (e.g. Anbar & Anbar, 1982; Breitmeyer & Ganz, 1976; Francis, 2003; Weisstein, 1968), on the other hand, often lack a spatial dimension and can therefore not account for the spatial interactions between the simultaneous and the temporal mask. For the same reasons, the effect of the length of the elements of the simultaneous mask poses a problem to these models.

In terms of perceptual organization, the interactions between the target and the masks can be understood from the grouping of the different elements. For example, when just the target and the simultaneous mask are presented together, their elements will group into one large grating. Such grouping only takes place when the elements are sufficiently similar: The vernier target groups with mask elements of the same length, but not with longer mask elements. Once the target is grouped with the simultaneous mask, its features become less accessible. It is as if the visual system filters out the inside of the regular structure made up by the target and the simultaneous mask. Only elements at the edge of such a regular structure are still well accessible (Herzog & Koch, 2001; Sharikadze, Fahle, & Herzog, 2005). In our experiments, we used length as the spatial property to modulate grouping. It has been demonstrated that other factors, such as contrast polarity, color, and stereoscopic depth have similar effects (Sayim, Westheimer, & Herzog, 2008).

Grouping effects are also found between the simultaneous mask and the temporal mask, mediated by the length of their elements. Because the vernier elements of both masks are aligned, whereas the target vernier is offset horizontally, the temporal mask "replaces" the target vernier at short SOAs inside the group formed with the simultaneous mask. When this happens, the target vernier is "freed" from the debilitating effects of the grouping (Experiment 1). Grouping between the simultaneous and the temporal mask is strongest when the two are presented together (SOA=0ms) and weakens as the temporal distance increases. Our data suggest that a delay as short as 60ms suffices to break the grouping between the simultaneous and the temporal mask. Similar fast grouping effects were found for elements of a backward mask appearing in different orders (Herzog, Koch, & Fahle, 2001), for different masks presented one after another (Herzog et al., 2008) and in sequences of verniers with different offsets (Hermens et al., in press).

Because the brain operates by means of interactions between neurons, the above explanation in terms of grouping requires a complementary explanation in terms of neural computation. Simulations with a neural network model applying lateral inhibition and excitation suggests that no explicit grouping modules are needed to perform grouping operations (Hermens et al., 2008; Herzog et al., 2003), but that, instead, neural interactions alone suffice. The combination of inhibition and excitation highlights the outer edge of regular structures and suppresses information on the inside. As soon as the regularity is broken, for example by removing an element from the grating, or by increasing an element's length, this will result in the enhancement of the corresponding neural activity. This enhanced activity, due to the mask's irregularities, suppresses the activity from a leading or trailing target. The above suggests that although relatively complex interactions are found between the simultaneous and the temporal mask, they might derive from low-level neural processing.

Some theories of masking are based on more general models of visual perception. Masking can be used to explore, test, and elaborate such models. For example, the model used by Francis (1997) is a simplified version of the model used by Grossberg and colleagues to explore a wide variety of visual phenomena. The model has been used to explain properties of 3-D perception (Grossberg & Howe, 2003; McLoughlin & Grossberg, 1998), figure-ground distinctions (Grossberg, 1997), illusory contours (Grossberg & Mingolla, 1985), line motion (Baloch & Grossberg, 1997), brightness perception (Grossberg & Hong, 2006), aftereffects (Francis & Rothmayer, 2003), texture segmentation (Grossberg, Kuhlmann, & Mingolla, 2007), and visual persistence (Francis, Grossberg, & Mingolla, 1994). Likewise, the model by Bridgeman (1971, 1978) is based on the general principle of lateral inhibition. As a result, discoveries about the properties of masking apply to more than just detailed models of masking.

Implications for applications of masking. Both simultaneous and temporal masking techniques are frequently used tools for studying cognition and perception. Although it may not be intentional, many studies use both masking techniques together. Typical examples are target textures embedded in a surrounding texture followed by a backward masking texture, for example, in perceptual learning (e.g. Karni & Sagi, 1993; Schubö et al., 2001) and in texture discrimination (e.g. Caputo, 1998; Meinhardt, Schmidt, Persike, & Röers, 2004). Other examples are strings of random letters that have to be reported followed by a mask composed of letters or symbols, for example in pattern masking (Hellige et al., 1979; Turvey, 1973), in partial report (Sperling, 1960), and in studies on visual persistence (Di Lollo & Bischof, 1995). Resolving the kinds of interactions between simultaneous and temporal masking is not only of importance for applications of masking, but it is also of theoretical interest in investigations of spatio-temporal vision.

Our results show that both simultaneous and temporal masking effects (and their interactions) are much more complicated than most researchers realize. In studies that use masking to explore other phenomena, the masks are usually assumed to have a simple effect on the target (e.g., to weaken some internal representation). Here, we have shown that simultaneous and temporal masks can interact, which indicates that masking needs to be applied with great care, as noted by Eriksen (1980), "the use of a visual mask may seriously confound your experiment."

The present study has started to move beyond a cautionary warning toward an understanding of how different types of masks interact. We have demonstrated that many masking effects are influenced by perceptual grouping of the different masks. As such, this study provides the starting point for a better understanding of masking effects. Such knowledge should increase the ability of researchers to use masking (in various forms) to understand other cognitive and perceptual processes.

References

Anbar, S., & Anbar, D. (1982). Visual masking: A unified approach. *Perception*, *11*, 427–439.

Bach, M. (1996). The "Freiburg visual acuity test". Automatic measurement of visual acuity. *Optometry and Vision Science*, *73*, 49–53.

Bachmann, T. (1994). *Psychophysiology of Visual Masking: The Fine Structure of Conscious Experience*. Commack, New York: Nova Science Publishers, Inc.

Baloch, A. A., & Grossberg, S. (1997). A neural model of high-level motion processing: line motion and formotion dynamics. *Vision Research*, *37*, 3037–3059.

Breitmeyer, B. G., & Ganz, L. (1976). Implications of sustained and transient channels for theories of visual pattern masking, saccadic suppression, and information processing. *Psychological Review*, *83*(1), 1–36.

Breitmeyer, B. G., & Öğmen, H. (2006). *Visual masking: Time slices through conscious and unconscious vision*. Oxford University Press.

Breitmeyer, B. G., Rudd, M., & Dunn, K. (1981). Metacontrast investigations of sustained-transient channel inhibitory interactions. *Journal of Experimental Psychology: Human Perception & Performance*, *7*, 770–779.

Breitmeyer, B. G., Ziegler, R., & Hauske, G. (2007). Central factors contributing to para-contrast modulation of contour and brightness perception. *Visual Neuroscience*, *24*, 191–196.

Bridgeman, B. (1971). Metacontrast and lateral inhibition. *Psychological Review*, *78*(6), 528–539.

Bridgeman, B. (1978). Distributed sensory coding applied to simulations of iconic storage and metacontrast. *Bulletin of Mathematical Biology*, *40*, 605-623.

Briscoe, G., Dember, W., & Warm, J. (1983). Target recovery in visual backward masking: no clear explanation in sight. *Journal of Experimental Psychology: Human Perception & Performance*, *9*, 898–911.

Caputo, G. (1998). Texture brightness filling-in. *Vision Research*, *38*, 841–851.

Dember, W., & Purcell, D. (1967). Recovery of masked visual targets by inhibition of the masking stimulus. *Science*, *157*, 1335–1336.

Di Lollo, V., & Bischof, W. F. (1995). The inverse intensity effect in duration of visible persistence. *Psychological Bulletin*, *118*, 223–237.

Di Lollo, V., Enns, J. T., & Rensink, R. A. (2000). Competition for consciousness among visual events: the psychophysics of reentrant visual processes. *Journal of Experimental Psychology: General*, *129*(4), 481–507.

Duangudom, V., Francis, G., & Herzog, M. H. (2007). What is the strength of a mask in visual metacontrast masking? *Journal of Vision*, *7*(1), 1–10.

Eriksen, C. W. (1980). The use of a visual mask may seriously confound your experiment. *Perception & Psychophysics*, *28*(1), 89–92.

Foley, J. M., & Chen, C. C. (1999). Pattern detection in the presence of maskers that differ in spatial phase and temporal offset: threshold measurements and a model. *Vision Research*, *39*, 3855–3872.

Francis, G. (1997). Cortical dynamics of lateral inhibition: Metacontrast masking. *Psychological Review*, *104*, 572–594.

Francis, G. (2000). Quantitative theories of metacontrast masking. *Psychological Review*, *107*, 768–785.

Francis, G. (2003). Developing a new quantitative account of backward masking. *Cognitive Psychology*, *46*, 198–226.

Francis, G. (2007). What should a quantitative model of masking look like and why would we want it? *Advances in Cognitive Psychology*, *3*, 21–31.

Francis, G., Grossberg, S., & Mingolla, E. (1994). Cortical dynamics of feature binding and reset: Control of visual persistence. *Vision Research*, *34*, 1089–1104.

Francis, G., & Herzog, M. H. (2004). Testing quantitative models of backward masking. *Psychonomic Bulletin and Review*, *11*, 104–111.

Francis, G., & Rothmayer, M. (2003). Interactions of afterimages for orientation and color: Experimental data and model simulations. *Perception & Psychophysics*, *65*, 508–522.

Grainger, J., Bouttevin, S., Truc, C., Bastien, M., & Ziegler, J. (2003). Word superiority, pseudoword superiority, and learning to read: a comparison of dyslexic and normal readers. *Brain & Language*, *87*, 432-440.

Green, M. F., Nuechterlein, K. H., Breitmeyer, B., & Mintz, J. (2006). Forward and backward visual masking in unaffected siblings of schizophrenic patients. *Biological Psychiatry*, *59*, 446–451.

Grossberg, S. (1997). Cortical dynamics of three-dimensional figure-ground perception of two-dimensional figures. *Psychological Review*, *104*, 618–658.

Grossberg, S., & Hong, S. (2006). A neural model of surface perception: Lightness, anchoring, and filling-in. *Spatial Vision*, *19*, 263–321.

Grossberg, S., & Howe, P. D. L. (2003). A laminar cortical model of stereopsis and three-dimensional surface perception. *Vision Research*, *43*, 801–829.

Grossberg, S., Kuhlmann, L., & Mingolla, E. (2007). A neural model of 3d shape-from-texture: Multiple-scale filtering, boundary grouping, and surface filling-in. *Vision Research*, *47*, 634–672.

Grossberg, S., & Mingolla, E. (1985). Neural dynamics of form perception: Boundary completion, illusory figures, and neon color spreading. *Psychological Review*, *92*, 173–211.

He, S., Cavanagh, P., & Intriligator, J. (1996). Attentional resolution and the locus of visual awareness. *Nature*, *383*, 334–337.

Hellige, J. B., Walsh, D. A., Lawrence, V. W., & Prasse, M. (1979). Figural relationship effects and mechanisms of visual masking. *Journal of Experimental Psychology: Human Perception & Performance*, *5*, 88–100.

Hermens, F., Luksys, G., Gerstner, W., Herzog, M. H., & Ernst, U. (2008). Modeling spatial and temporal aspects of visual backward masking. *Psychological Review*, *115*, 83–100.

Hermens, F., Scharnowski, F., & Herzog, M. (in press). Spatial grouping determines temporal integration. *Journal of Experimental Psychology: Human Perception & Performance*.

Herzog, M. H. (2007). Spatial processing and visual backward masking. *Advances in Cognitive Psychology*, *3*, 85–92.

Herzog, M. H., Ernst, U., Etzold, A., & Eurich, C. (2003). Local interactions in neural networks explain global effects in the masking of visual stimuli. *Neural Computation*, *15*, 2091–2113.

Herzog, M. H., Fahle, M., & Koch, C. (2001). Spatial aspects of object formation revealed by a new illusion, shine-through. *Vision Research*, *41*, 2325–2335.

Herzog, M. H., & Koch, C. (2001). Seeing properties of an invisible object: feature inheritance and shine-through. *Proceedings of the National Academy for Science, USA*, *98*, 4271–4275.

Herzog, M. H., Koch, C., & Fahle, M. (2001). Shine-through: temporal aspects. *Vision Research*, *41*, 2337–2346.

Herzog, M. H., Schmonsees, U., Boesenberg, J. M., Mertins, T., & Fahle, M. (2008). Fast perceptual grouping in the shine-through effect. *Perception & Psychophysics*, *70*(5), 887–895.

Karni, A., & Sagi, D. (1993). The time course of learning a visual skill. *Nature*, *365*, 250–252.

Li, Z. (2000). Pre-attentive segmentation in the primary visual cortex. *Spatial Vision*, *13*(1), 25–50.

Macknik, L. M., & Martinez-Conde, S. (2007). The role of feedback in visual masking and visual processing. *Advances in Cognitive Psychology*, *1-2*, 125–152.

Malania, M., Herzog, M. H., & Westheimer, G. (2007). Grouping of contextual elements that affect vernier thresholds. *Journal of Vision*, *7*(2), 1–7.

McLoughlin, N. P., & Grossberg, S. (1998). Cortical computation of stereo disparity. *Vision Research*, *38*, 91–99.

Meinhardt, G., Schmidt, M., Persike, M., & Röers, B. (2004). Feature synergy depends on feature contrast and objecthood. *Vision Research*, *44*, 1843–1850.

Öğmen, H. (1993). A neural theory of retino-cortical dynamics. *Neural Networks*, *6*, 245–273.

Öğmen, H., Breitmeyer, B., & Melvin, R. (2003). The what and where in visual masking. *Vision Research*, *43*, 1337–1350.

Öğmen, H., Breitmeyer, B. G., Todd, S., & Mardon, L. (2006). Target recovery in metacontrast: The effect of contrast. *Vision Research, 46*, 4726–4734.

Palmer, S. E., Brooks, J. L., & Nelson, R. (2003). When does grouping happen? *Acta Psychologica*, *114*(3), 311-330.

Robinson, D. N. (1966). Disinhibition of visually masked stimuli. *Science*, *154*(745), 157-158.

Saarela, T. P., & Herzog, M. H. (2008). Time-course and surround modulation of contrast masking in human vision. *Journal of Vision*, *8*(23), 1–10.

Sayim, B., Westheimer, G., & Herzog, M. H. (2008). Contrast polarity, chromaticity, and stereoscopic depth modulate contextual interactions in vernier acuity. *Journal of Vision*, *8*(8), 1–9.

Schubö, A., Schlaghecken, F., & Meinecke, C. (2001). Learning to ignore the mask in texture segmentation tasks. *Journal of Experimental Psychology: Human Perception & Performance*, *27*, 919–931.

Sharikadze, M., Fahle, M., & Herzog, M. H. (2005). Attention and feature integration in the feature inheritance effect. *Vision Research*, *45*, 2608-2619.

Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied*, *74*(11), 1–29.

Taylor, M. M., & Creelman, C. D. (1967). PEST: Efficient estimates on probability functions. *The Journal of the Acoustical Society of America*, *41*, 782–787.

Tenkink, E. (1983). Recovery at short intervals between masking flashes. *Vision Research*, *23*, 1693–1698.

Tenkink, E., & Werner, J. (1981). The intervals at which homogeneous flashes recover masked targets. *Perception & Psychophysics*, *30*, 129–132.

Turvey, M. T. (1973). On peripheral and central processes in vision: Inferences from an information-processing analysis of masking with patterned stimuli. *Psychological Review*, *80*, 1–52.

Weisstein, N. (1968). A rashevsky-landahl neural net: simulation of metacontrast. *Psychological Review*, *75*(6), 494–521.

Weisstein, N., & Bisaha, J. (1972). Gratings mask bars and bars mask gratings: visual frequency response to aperiodic stimuli. *Science*, *176*, 1047–1049.

Westheimer, G., & Hauske, G. (1975). Temporal and spatial interference with vernier acuity. *Vision Research*, *15*, 11371141.

Wilkinson, F., Wilson, H. R., & Ellemberg, D. (1997). Lateral interactions in peripherally viewed texture arrays. *The Journal of the Optical Society of America A*, *14*, 2057–2068.

Zhaoping, L. (2003). V1 mechanisms and some figure-ground and border effects. *Journal of Physiology, Paris*, *97*, 503–515.